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EFFECT OF COIL DESIGN ON TUBE DEFORMATION IN ELECTROMAGNETIC FORMING

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ABSTRACT

Electromagnetic compression is a high energy rate forming process; in which workpiece in the form of tubes are deform using energy from capacitor bank. This process is a contact free process. It is a solid state forming process. At quasi state condition, less formability of material is found and it create drawback in the form of springback, wrinkling and non-uniform thickness. But at high strain rate materials like 5xxx, 6xxx and 7xxx shows an excellent formability and reduced the springback, wrinkling and enhanced the surface quality. In the present work, electromagnetic compression of Al6061 tube has been carried out experimentally as well as analytically using finite element method simulation. The objective of the deformation is to study the effect of number of turns and axial length of coil on deformation. Al6061 tubes of 56 mm outer diameter (OD) and 0.85 mm thickness were compressed using a four-turn, five-turn and six-turn compression coil using 40 kJ capacitor bank. Compression of the tube is done with the help of capacitor bank charged to 2.3 kJ at 9 kV.

KEYWORDS: Compression Coil, Electromagnetic Forming, FE Analysis, Aluminum AA6061 & Strain Rate

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Original Article

1. INTRODUCTION

Global fuel scenario set a goal for automotive industries to achieve reduced weight of body parts in order to reduce emission and create healthy environment for human being. Light weight alloys play a vital to tackle the problem [1]. Conventional methods have some shortcoming and they are not capable to make complex parts with new materials. Some of the challenges in convention forming process are springback, wrinkling, low formability and non-uniform thickness of workpiece etc. The problems can be minimized by high energy rate forming process. Researchers and industries are getting sector attract towards this area because of these advantage. Tubes and sheet metal forming are an integral part of automotive, aerospace and other industries. Therefore researchers have been working on different aspects of sheet and tube metal forming using high strain rate forming methods. Xiong et al. [2] presented dual coil for forming of tube and also used two power sources to form tube using the Lorentz force. The effectiveness of the system was initially verified theoretically and then numerically. Lai et al., [3] focused on the potential effects of coil polarity and comparison of the process experimentally and numerically using a dual coil. Final result of this work is useful for coil polarity selection. Ghadami and Dariani [4] investigated tube expansion by high strain rate forming like electromagnetic forming and liquid shock tube forming. Both analytical and numerical models are used for validation. Liu et al., [5] suggested electromagnetic incremental forming (EMIF) for large parts of aluminum alloy (Al5052-O)

using dual coil. An ellipsoidal parts was successfully manufactured by EMIF method. Qiu et al., [6] suggested electromagnetic incremental forming, space-time controlled multi-stage pulsed magnetic field forming, Electromagnetic tube expansion are used for analyzing magnetic force and deformation behavior of the tube and sheet. Ma et al., [7] studied effect of discharge voltage, lubrication on thickness and strain distribution of AA 5052 and AA5754 sheets in free forming using the electromagnetic forming (EMF) process and emphasized that the emphasis inertia effect on deformation play a vital role in EMF. Vivek et al., [8] reported steel tube compression using the 9 turn helical solenoid coil. Photon Doppler Velocimetry (PDV) was used to find out the velocity of tube. Chunfeng et al., [9] reported tube bulging carried out by numerically (employing FEM simulation) and effect of magnetic pressure on it with the help of ANSYS software. Magnetic pressure distribution was also investigated in the direction of tube thickness. Bartels et al., [10] investigated comparison between two algorithms on FEM. That is loose-coupled algorithm and sequential-coupled algorithm and found sequential-coupled algorithm more accurate than the loose-coupled algorithm. Ahmed et al., [11] proposed flat coil design and distribution of magnetic field over the blank. The comparative study between magnetic force, magnetic field and current density also studied using FEM. Patel and Kore [12] proposed dual electromagnetic forming process. Uniform pressure coil was used for improved the system performance. Chu and Lee [13] claimed to design a field shaper design for sheet metal impact forming. Effect of different slit width also analyzed and found that wider slit reduced the magnetic effect and it is not suitable for joining. Zittel [14] focused on the high speed metal forming process and its industrial applications. Aircraft control rod, medical instrument and aircraft torque tube are the specific application of the high speed metal forming process. Geier et al., [15] suggested interference-fit joining of AA6082-O tube and mandrel made of AA6082-O, AISI1045 and Erlaton 6SA. Strength of interference-fit joints was also investigated. Kim et al., [16] carried out expansion of Al 3000 (0.2 mm thickness) tube using EMF process. Two coils with constant pitch but different gap (0.18 and 0.38 mm) (gap between coil and workpiece) and two dies were used for experiments. Enhancement of formability of Al 3000 has been found to be 10%. Tak et al., [17] developed metal shaping application for Al 6061 tube using the preheating wokpiece and process. Displacement along the distance direction increases when its temperature rises from 200°C to 250°C. Kuo et al., [18] reported decrease in magnetic field density during the raising of coil temperature. Raising of coil temperature effect the productivity.

From above discussions, it can be concluded that tube compression work is not enough or limited. In present study effect of coil design on the output parameter like velocity, strain, magnetic field on workpiece (tubular) and deformation of the tube have been analyzed. Three variant design of coil have considered for the study. Out of that, a single design of the coil as shown in Figure 1, have been verified by both experimental and FE analysis. Other two coil have been analyzed using FE analysis. Finite element analysis has been carried out to determined magnetic field, resultant deformation velocity, displacement, and effective strain and the parameters have co-related.

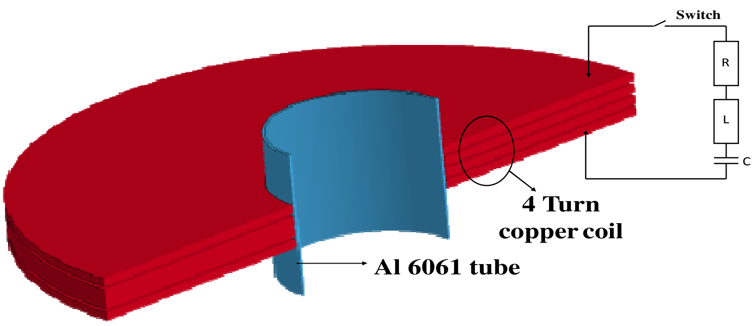


Figure 1: Four Turn Electromagnetic Tube Compression.

2. EXPERIMENTAL

2.1 Materials and Workpiece Geometry

A four turn compression coil was used for experiments. Electromagnetic forming (EMF) machine of 40 kJ, 20 kV was used. Al 6061 tube having a length of 52 mm with 0.85 mm tube thickness is used for the study to deform tube using different coil. Al 6061 is a structural which find application, in automobile, aerospace and strategic areas. The coil is made up of OFHC copper. The material properties of both Al 6061 and copper given in Table1. Chemical composition of Al 6061 is given in Table 2.

Table 1: Mechanical Properties of Copper and Aluminum [19 and 20]

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Copper- Coil	8960	124	0.34
Aluminum- tube	2700	69	0.33

Table 2 Chemical Composition of Al6061-T6 (By weight %)
[Determined by Optical Emission Spectrometer]

Si	Fe	Mg	Cu	Mn	Al
0.73	0.57	0.51	0.18	0.092	Remaining

2.2 Finite Element Analysis

Simulation work carried out using commercially available LS-DYNA software to validate the experimental result and find out its effect on tube compression using given coil. Sectioned view of FE model of coil with 4, 5 and 6 turn have been shown in Figure 2. The material properties as given in Table 1 is used for simulation.

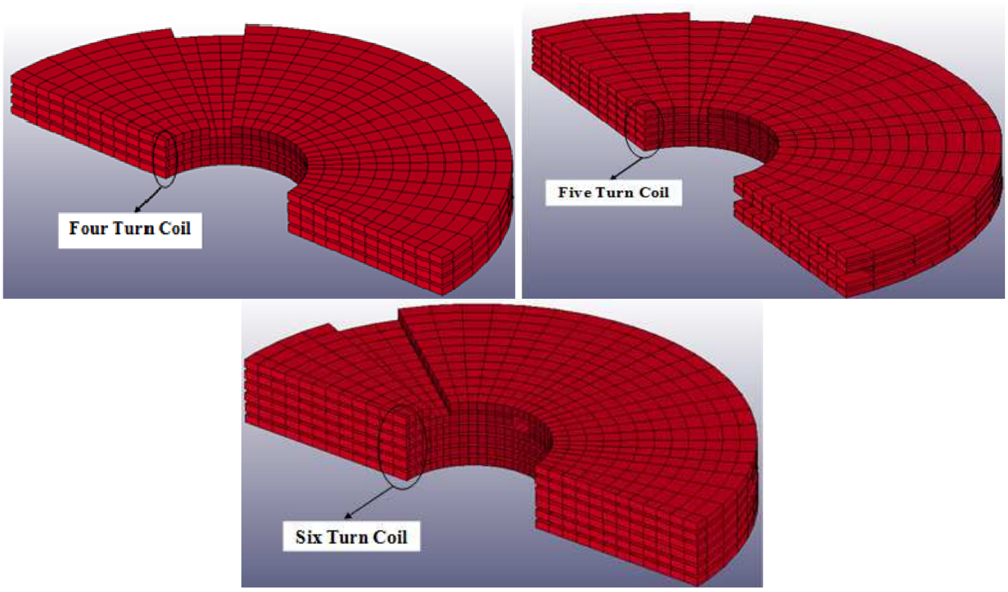


Figure 2: FE Model of Different Turns of Compression Coil.

2.3 Experimental Setup

For experiments, only 2.3 kJ at 9 kV energy was used. The gap between coil and tube was 0.5 mm in experiments. Experiments are performed at double wire single capacitor bank. The coil internal diameter (ID) was 57 mm and outer diameter of 200 mm. A schematic of the setup is shown in Figure 3. It consist of capacitor bank, a charging system and discharging system (i.e. coil).

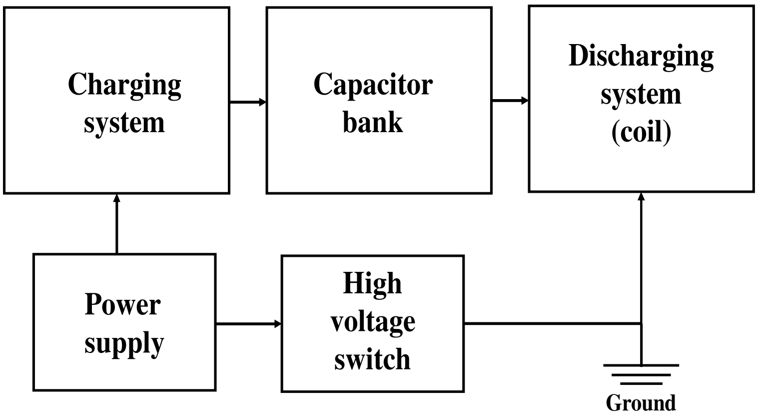


Figure 3: Schematic Experimental Setup of Electromagnetic Compression.

3. METHODOLOGY

Different coil has been taken for the study. Axial length has been measured by digital vernier with 0.01 mm least count. Measured value is shown in Table 3. Effect of number of turns and axial length has been analyzed by deforming an Al6061 tube by both experiments and FE analysis. The details of the coil considered for the study is shown in Table 3. Discretization (meshing) have been carried out using 3D hexahedral element. Number of elements have been decided on the basis of convergence analysis and the same have been shown in Table 3. Various LS-DYNA cards are used for the simulation. MAT_ELASTIC_001, MAT_PIECEWISE_LINEAR_PLASTICITY_024 and EM_CIRCUIT_ROGO are typical cards used to define material properties and circuit parameter in the model. From the simulation study magnetic field, resultant deformation velocity, displacement and effective strain were analyzed. FE simulation have been carried out to see the effect these coil on various parameter as discussed as earlier. Result of coil1 have been validated through experiments.

Table 3: Details of Elements in Different Number of Turns

Coil Details		Coil (OD/ID) mm 200/57		Tube (OD/ID) mm 56/54.3
Coil Designation	Axial Length of Coil	Number of Turns	Number of Elements	Number of Elements
Coil1	15.6	4	2940	17888
Coil2	19.8	5	2772	17888
Coil3	24	6	4524	17888

4. RESULTS AND DISCUSSIONS

Effects of coil design in terms of number of turns and axial length have been analyzed by both experiments and FE simulation. Three coil design (as given in Table 3) have been considered in the study. Only one case of coil design have been validated experimentally. A tubular workpiece is deformed using 2.3 kJ/9 kV energy. High current passing through circuit is opted using the rogowski coil, shown in the Figure 4. The peak of the current of 52 kA is obtained with the given capacitor bank.

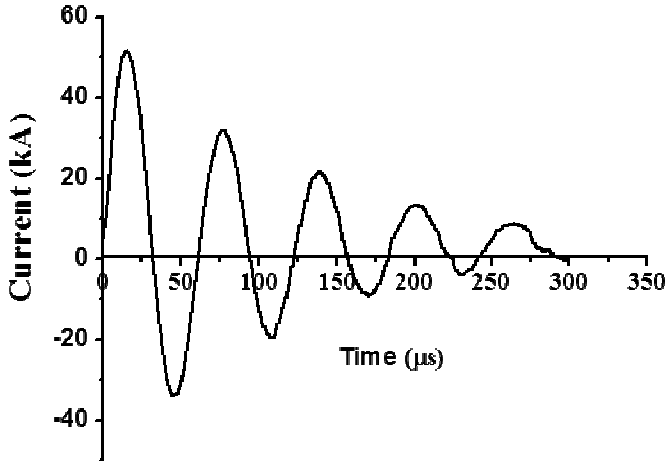


Figure 4: Current Waveform at 2.3 kJ.

Result of both experiments and simulation have been tabulated and shown in Table 4

Table 4

Coil	Initial Diameter of Workpiece OD (mm)	Simulated Final Diameter of Workpiece OD (mm)	Experimental Final Diameter of Workpiece OD (mm)	Percentage Difference
Coil1 (4 turn)	56	50.94	51.13	0.37
Coil2 (5 turn)	56	46.46	Experiments not performed	
Coil3 (6 turn)	56	42.59		

It can be seen that diameter obtained in both experiment and FE simulation is very close and then the result is validated. Diameter of tube decreases as the number of turns increases as seen from the Table4 for results obtained in FE simulation. Magnetic field increases from 9.11 to 10.7 T as the number of turns increases from 4 to 6. Similarly, pattern observed in effective plastic strain. Resultant displacement increases to approximately double value when the number of turns increases from 4 to 6. There is a significant increase in velocity as the number of turn increases from 4 to 6. The plot of these parameters with respect to time of deformation is also shown in Figures 5 (a), (b), (c) and (d). These plots shows validations in similar line. The magnetic field increases to its peak value in just 15 μs but the velocity lags slightly with respect to magnetic field. Velocity attains maximum value at about 23-25 μs. it is also observed that the rise time for velocity increases as the number of turns increases from 4 to 6. The tube attains maximum value of displacement and effective plastic strain at shorter deformation time for lower number of turns. Thus, the analysis shows that there is significant effect of FE analysis is also carried out to correlate different process parameters like magnetic field, displacement, effective plastic strain and resultant velocity with respect to different coil design taken in the study. The results shows that there is huge effect of coil design on deformation and the process parameter.

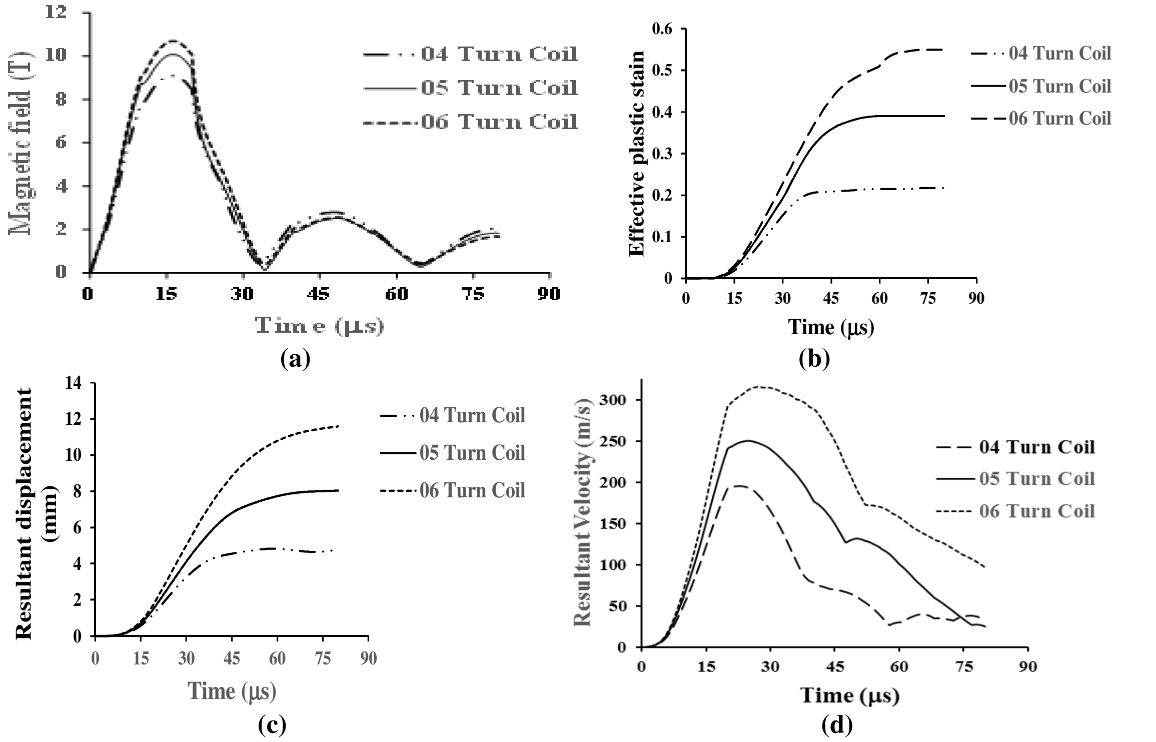


Figure 5: (a) Magnetic Field (b) Effective Plastic Strain (c) Resultant Displacement (d) Resultant Velocity

Figure 6 shows the deformed tube in comparison with simulated tube for coil. The contour of the simulated tube is shown in displacement fringe value similarly, in crest and ridge in both experimental and simulated sample validates the results. The contour of the tube deformed using other coils i.e. coil2 and coil3 is also shown in the Figure. Results of FE analysis in terms of magnetic field, effective plastic strain, displacement and resultant velocity have been listed in Table 5. It can be seen that the peak value of the parameters. It can be seen that the peak value of all parameters increase as the number of turns increases.

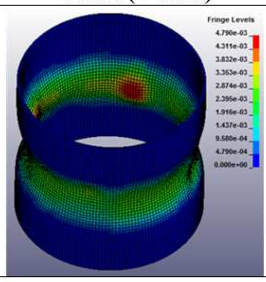
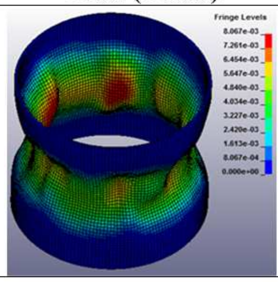
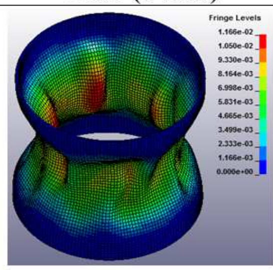
Double wire single capacitor bank at 2.3 kJ			
Experimental	Simulation		
Coil1 (4 turn)	Coil1 (4 turn)	Coil2 (5 turn)	Coil3 (6 turn)
			

Figure 6: Experimental And Simulated Tube Deformation.

Table 5: Peak Values of Parameters for different Types of Coil

Parameters	Coil1 (4 turn)	Coil2 (5 turn)	Coil3 (6 turn)
Magnetic field (T)	9.11	10.1	10.7
Effective plastic strain	0.217	0.39	0.549
Displacement (mm)	4.83	8.03	11.6
Resultant velocity (m/s)	196	250	316

5. CONCLUSIONS

It is important to understand the effect of coil design on deformation of workpiece in electromagnetic forming process. The present study aims to analyze the effect of number of turns and axial length on deformation of tube. Following are some conclusions drawn from the work.

- There is a significant effect of number of turns on the various parameters of electromagnetic forming of tube. As number of turn's increases from 4 to 6 the deformation increases.
- Increase in number of turns increases the axial length of coil, and thereby increasing the deformation zone on the tube.
- The result of FE analysis in terms of deformation of the tube by one of the coil i.e. coil with number of terms 4 has been validated with experiment. The difference in the value is within 1%.
- Parameter like velocity, deformation, effective plastic strain and displacement are computed using FE analysis method. It was found that there is increase in the value of these parameters when number of turn's increases from 4 to 6.

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